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Transcranial direct current stimulation of the posterior parietal cortex modulates arithmetic learning

Running title: Modulation of arithmetic learning

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Abstract

The successful acquisition of arithmetic skills is an essential step in the development of mathematical competencies and has been associated with neural activity in the left posterior parietal cortex (PPC). It is unclear, however, whether this brain region plays a causal role in arithmetic skill acquisition and whether arithmetic learning can be modulated by means of non-invasive brain stimulation of this key region. In the present study we addressed these questions by applying transcranial direct current stimulation (tDCS) over the left PPC during a short-term training that simulates the typical path of arithmetic skill acquisition (specifically the transition from effortful procedural to memory-based problem-solving strategies). Sixty participants received either anodal, cathodal, or sham tDCS while practicing complex multiplication and subtraction problems. The stability of the stimulation-induced learning effects was assessed in a follow-up test 24 hours after the training. We found that the learning progress was modulated by tDCS. Cathodal tDCS (compared to sham) decreased learning rates during training and resulted in poorer performance which lasted over 24 hours after stimulation. Anodal tDCS showed an operation-specific improvement for subtraction learning. Our findings extend previous studies by demonstrating that the left PPC is causally involved in arithmetic learning (and not only in arithmetic performance) and that even a short-term tDCS application can modulate the success of arithmetic knowledge acquisition. Moreover, our finding of operation-specific anodal stimulation effects suggests that the enhancing effects of tDCS on learning can selectively affect just one of several cognitive processes mediated by the stimulated area.

Introduction

Mathematical competencies are of utmost importance for educational and occupational success (Parsons & Bynner, 2005; Gross *et al.*, 2009). An essential step in their development lies in the acquisition of arithmetic skills in school, which is typically characterized by a transition from effortful procedural problem-solving strategies (such as counting or other magnitude processing procedures) to efficient memory-based strategies (i.e., retrieval of arithmetic facts from memory; Siegler *et al.*, 1996). The application of such memory-based strategies predicts childrens' later mathematical competencies (Price *et al.*, 2013) and represents a hallmark deficit in children with mathematical learning disabilities (Geary, 2013). Several neuroimaging studies have revealed that arithmetic skill acquisition is strongly associated with the functioning of the posterior parietal cortex (PPC; Ansari, 2008; Grabner *et al.*, 2009; Zamarian *et al.*, 2009). First, developmental studies have revealed an increasing reliance on the PPC during arithmetic problem solving with increasing age, which was interpreted as evidence of an increasing functional specialization (Rivera *et al.*, 2005; Kaufmann *et al.*, 2011). And, second, the intensive training of arithmetic problems has been found to be accompanied by activation increases in the PPC (Delazer *et al.*, 2003; Ischebeck *et al.*, 2007; Zamarian *et al.*, 2009). Against this background, there is increasing interest into the questions of whether the PPC is causally involved in this learning process and whether modulation of its activity by means of non-invasive brain stimulation impacts on arithmetic learning.

Previous brain stimulation studies using transcranial magnetic stimulation (TMS) have provided first evidence suggesting that the PPC plays a causal role for the performance in arithmetic tasks. **TMS induces electrical current in the brain by applying strong magnetic fields (Sandrini *et al.*, 2011). Previous studies with repetitive TMS (stimulation with magnetic pulse trains, which depending on the stimulation protocol can either excite or inhibit cortical areas) have revealed that the inhibition of the PPC results in longer response latencies while solving arithmetic problems compared to control conditions (Göbel *et al.*, 2006; Andres *et al.*, 2011; Salillas *et al.*, 2012).** For instance, Göbel *et al.* (2006) reported that repetitive TMS over the left PPC induced longer response latencies while participants solved complex addition problems (two-digit plus two-digit problems).

In contrast to the TMS literature, the evidence from studies applying transcranial electrical stimulation (tES) over the PPC is scarce and inconsistent. **TES subsumes non-invasive brain stimulation methods in which a small electrical current (typically around 1-2 mA) is applied to the brain through electrodes attached to the scalp (Nitsche *et al.*, 2008). The most frequently used type of tES is transcranial direct current stimulation (tDCS), in which a constant direct current is applied through an anode (assumed to increase the excitability of the underlying cortical region) and a cathode (assumed to decrease its excitability). In the domain of arithmetic, tDCS over the PPC has been applied in five studies so far. Hauser *et al.* (2013) reported that anodal stimulation of the left PPC resulted in performance improvements (in terms of faster responses) in a two-digit subtraction task. Rütsche *et al.* (2015) replicated this finding in a subtraction as well as addition task, but also observed that left anodal stimulation resulted in performance decreases (in terms of solution rate) in simple (one-digit) addition and subtraction problems. Klein *et al.* (2013) and Artemenko *et al.* (2015) did not find general stimulation effects on performance in complex (two-digit) addition problems after bilateral and unilateral tDCS, respectively. However, they revealed modulations of arithmetic processes related to magnitude processing (Klein *et al.*, 2013) and the processing of the place-value structure of Arabic digits (Artemenko *et al.*, 2015). Finally, Clemens *et al.* (2013) failed to find significant performance changes in a simple multiplication task after anodal stimulation of the left PPC.**

Most importantly, all previous stimulation studies have only investigated effects of brain stimulation over the PPC on the *performance* in arithmetic tasks but not on the *acquisition* of arithmetic knowledge and skills (i.e., arithmetic learning). Given the strong need to better understand the role of the PPC in successful mathematics learning and the rising discussions about tES as a potential remediation tool for (mathematical) learning disorders (Cohen Kadosh *et al.*, 2013; Krause & Cohen Kadosh, 2013), an evaluation of the effects of tES over the PPC on arithmetic learning is urgently needed. The present study is the first to address this issue.

To this end, we applied a well-established arithmetic fact training which mimics the typical transition from procedural to memory-based strategies in arithmetic. Participants were presented repeatedly with small sets of complex multiplication (two-digit times one-digit) and subtraction (two-digit minus two-digit) problems. At the beginning of the training, these problems are generally solved by procedural strategies (the solution needs to be calculated). With increasing practice, the problems are progressively stored as arithmetic facts in memory and solved through fact retrieval, which is reflected in faster and more accurate responses. This arithmetic fact training has been repeatedly administered in neuroimaging studies and consistently found to be accompanied by activation increases in the left PPC (for a review, cf. Zamarian *et al.*, 2009). During training, three groups of participants received 30 minutes of either anodal, cathodal, or sham tDCS over the left PPC. To assess the stability of the stimulation-induced learning effects, we measured performance on both trained as well as untrained problems 24 hours after the training and stimulation session. Untrained problems were included to test the task-specificity of the stimulation.

As it is assumed that anodal stimulation increases the excitability of the underlying cortical area (Nitsche & Paulus, 2000), we hypothesized that anodal tDCS should increase the learning performance. **Although cathodal stimulation is generally assumed to decrease the excitability of the underlying cortical area (Nitsche & Paulus, 2000), this assumption has mainly been confirmed in motor tasks (Jacobson *et al.*, 2012). Therefore, the hypothesis that cathodal stimulation impairs the learning performance can only be postulated conditionally.**

Materials and Methods

Participants

Sixty-five healthy, right-handed adult students at the University of Zurich or the ETH Zurich participated in the present study. They had neither a history of neurological or psychiatric diseases nor a mathematical learning disability. Five subjects had to be excluded due to a lack of training motivation (e.g., decreasing performance with training), resulting in a sample of 60 participants

(30 females; age: 21.98±2.99 years). The average students' numerical-mathematical IQ, as tested by means of the arithmetic subscale of the intelligence structure test 2000R (Amthauer *et al.*, 2001), was 106.38 (SD = 15.67). The ethics committee of the canton of Zurich, Switzerland, approved the study. All subjects were thoroughly informed about the study, gave written informed consent and were paid 70 CHF for their participation.

Materials and procedure

The experiment included two sessions: In the learning session, participants learnt the solutions of 5 complex multiplication and 5 complex subtraction problems over 45 minutes. Then, 24 hours after the learning session, a performance session took place in which participants were presented with old (trained) as well as new (untrained) multiplication and subtraction problems over 30 min. Both the learning and the performance session took place in a group laboratory.

In the learning session, the problem selection and training procedure were similar to previous neuroimaging studies of arithmetic fact training (Grabner *et al.*, 2009). The multiplication problems were two-digit times one-digit problems with two-digit solutions (e.g., 12x7=84). The subtraction problems were two-digit minus two-digit problems with two-digit solutions (e.g., 52-15=37). Problems did not include numbers divisible by ten as operands or as solutions. Participants were presented with the problems on a computer screen and were required to type in the answer as fast and as accurately as possible using the numerical keypad of the keyboard (Fig. 1). After the response was confirmed (with the ENTER key), a feedback (including the correct solution) was provided for 1000 ms. A short typing training preceded the experiment in order to familiarize subjects with the number keypad. The problems were presented in blocks of 20 items. To avoid strong switching effects between operations, each block included 5 problems of the same operation presented 4 times in random order. The blocks with the two operations were presented in alternate order. Overall, each of the 5 multiplication and 5 subtraction problems was presented 36 times. To increase training motivation and progress, feedback on the number of correctly solved problems and the average response latency was presented for 7500 ms after every block. Participants were instructed to increase their speed and accuracy during the training.

In the performance session, no feedback was provided. Each block consisted of 5 trained and 5 untrained problems of the same operation and was followed by a pause of 5000ms. Similar to the learning session, blocks of the two operations were alternated. Each trained problem was presented 12 times. In addition, 15 untrained multiplication problems and 15 untrained subtraction problems of similar complexity were presented, each repeated 4 times.

At the end of each session, a brief questionnaire was administered in which participants indicated their assumption about which stimulation condition they received. Analyses of the correspondence between actual and assumed stimulation conditions revealed that participants were not able to guess their stimulation condition above chance, neither in the learning session (contingency coefficient of .31, p = .37), nor in the performance session (contingency coefficient of .34, p = .27).

Transcranial direct current stimulation

TDCS was applied by means of a multi-channel DC stimulator (NeuroConn GmbH, Ilmenau, Germany). In each participant, the **current was applied on the head surface using two rubber electrodes covered with saline-soaked sponges. The active electrode (7x5 cm) was centered over positions P5 and CP5 of the extended 10-20 system for scalp electrodes, as determined using individually placed standardized EEG caps. The cortical projections of these positions have been shown to lie in the PPC (e.g., Herwig *et al.*, 2003; Koessler *et al.*, 2009).** The reference electrode was placed over the right supraorbital area and was chosen to be large (10x10 cm) to reduce current density to levels that are functionally ineffective (Nitsche *et al.*, 2007; Nitsche *et al.*, 2008). **To ensure that our electrode setup effectively stimulated the PPC, we modelled the current flow and density using the Comets Toolbox (Jung *et al.*, 2013). As illustrated in Fig 2, the simulation suggests that the left PPC was indeed most strongly affected by the applied montage. In contrast, the effects of stimulation on the areas underlying the reference electrode were weaker and more diffuse. The maximal current**

densities at the reference electrode were well in the range of the lowest possible threshold (0.017 mA/cm²) where stimulation effects could be found in the motor domain (Nitsche & Paulus, 2000). Thus, we can be confident that our behavioral effects are indeed driven by stimulation of the PPC.

In the learning session, participants were randomly allocated to the three stimulation conditions. Group 1 received anodal, group 2 received cathodal, and group 3 received sham stimulation (each group's n=20). In the performance session, all three groups received sham stimulation. **Participants were blinded with respect to the stimulation type in both sessions. Specifically, they were informed that they will receive one of the three different stimulation conditions, randomly chosen in each session without further specification. At least 3 of 4 experimenters were present during each session, with the specific combination of experimenters slightly differing across sessions. Experimenters were blind with respect to which participant received active or sham stimulation.**

Anodal and cathodal tDCS was applied for 30 min at 1.5 mA intensity, whereas sham tDCS was applied for 30 s at the same intensity. In all conditions, fade-in and fade-out periods of 10 s were employed during which the current intensity was linearly increased or decreased. Using this procedure, active and sham stimulation are typically not distinguishable (Nitsche *et al.*, 2008). The experimental paradigm (training in the training session and task in the performance session) was started 3 minutes after the beginning of the stimulation to allow for physiological stabilization of the tDCS effects.

Data analysis

Data were analyzed using MATLAB R2010b (The MathWorks Inc.) and SPSS for Windows Version 22 (IBM Corp). Mixed ANOVAs were computed as General Linear Models with repeated measures. Effect sizes in the ANOVAs represent partial eta squared (η_p^2) values. In case of significant effects of stimulation in the ANOVAs, post-hoc comparisons (LSD tests, one-sided) were computed to test the directed hypotheses that anodal tDCS increases learning and that cathodal tDCS decreases learning. Effect sizes for significant post-hoc comparisons are given as Cohen's d.

Learning session

We used a power law function (Delaney *et al.*, 1998) to determine the learning effect in reaction times and correct responses for each individual participant:

$$y_N = \alpha N^{-\beta}, \tag{1}$$

where y is the fitted performance, β describes the individual learning rate, N denotes the block number (each block consisted of 20 problems), and α is the offset of the curve, which approximates the performance in the first block. For each subject, we fitted the power law to the median reaction time of the correct responses or solution rate of each block by minimizing the root-mean square deviation (RMSD). Multiplications and subtractions were fitted independently.

To determine how well the behavior was reflected by the power law function, we used Bayesian model selection (Stephan *et al.*, 2009) to compare the model fit (RMSD) with an exponential model:

$$y_N = \alpha e^{-\beta(N-1)} \tag{2}$$

and a linear model:

$$y_N = \alpha + N\beta. \tag{3}$$

For reaction times, the power law clearly outperformed the other two models (Table 1). We therefore quantified the impact of tDCS on learning by comparing the parameters β between stimulation conditions (anodal, cathodal, sham) and operations (subtraction, multiplication) using mixed ANOVA. To ensure that the groups did not differ in their initial performance, we compared the model offset α using mixed ANOVA.

For solution rates, there was no clear winning model for subtractions as well as for multiplications. We therefore quantified the effect of learning as the improvement between the first and the last training block using similar mixed ANOVAs as for the learning parameters.

Performance session

To evaluate whether the effects of stimulation were persistent and specific to the trained problems, we compared the solution rates as well as the median reaction times for the correct trials using a mixed ANOVA with the factors stimulation (i.e., stimulation in the learning session: anodal, cathodal, sham), operation (subtraction, multiplication) and training (trained, untrained).

Results

Learning session

Response latencies

Participants in all three stimulation conditions showed identical performance at the start of the learning session (parameter α, main effect of stimulation: $F(2,57)<.01$, $p>.99$, $\eta_p^2<.01$). Subtractions (α = 3333) were solved more slowly than multiplications (α=2920; main effect of operation: $F(1,57)=10.26$, $p<.01$, η_p^2=15). However, this difference in response times between operations did not differ between the three stimulation groups (interaction of operation and stimulation: $F(2,57)=0.76$, $p=.47$, $\eta_p^2=.03$), thereby confirming similar patterns of performance at the start of the learning session.

In line with our expectations, learning rates were significantly affected by the type of stimulation (parameter β, main effect of stimulation: $F(2,57)=3.75$, $p<.05$, $\eta_p^2=.12$; Fig. 3a). Post-hoc comparisons revealed that cathodal stimulation (β=.41) slowed down learning compared to sham (β=.48; d = 0.71) and anodal (β=.49; d = 0.85) stimulation (both ps<.05). Anodal stimulation did not significantly enhance the learning rate compared to sham (p=.38). Multiplication problems (β=.49) were learned significantly faster than subtractions (β=.43; main effect of operation: $F(1,57)=9.92$, $p<.01$, $\eta_p^2=.15$). The effects of cathodal stimulation on arithmetic learning were similarly expressed during both types of arithmetic operations (interaction of operation and stimulation: $F(2,57)=0.44$, $p=.65$, $\eta_p^2=.02$). Thus, cathodal stimulation over PPC slowed down learning of both types of arithmetic operations to a similar degree, despite differences between both operations in overall learning rates and overall response times at the start of the experiment.

Solution rates

As for the reaction times, we found that solution rates did not differ between the three stimulation groups at the beginning of the experiment (main effect of stimulation: $F(2,57)=1.07$, $p=.35$, $\eta_p^2=.04$). Solution rates also did not differ between multiplication and subtraction problems (main effect of operation: $F(1,57)=.25$, $p=.62$, $\eta_p^2<.01$), in neither stimulation group (interaction of stimulation and operation: $F(2,57)=2.42$, $p=.10$, $\eta_p^2=.08$). Thus, participants in the different stimulation groups started the learning session with similar levels of initial performance.

Learning rates in solution rates were also affected by stimulation, but now in a way that depended on the type of arithmetic operation (interaction of operation and stimulation: $F(2,57)=5.07$, $p<.01$, $\eta_p^2=.15$; main effect of stimulation: $F(2,57)=0.98$, $p=.38$, $\eta_p^2=.03$; Fig. 3b). For the subtraction problems, anodal stimulation (solution rates +19%) resulted in increased learning compared to sham stimulation (+6%; $d = 0.58$) or cathodal stimulation (+3%; $d = 0.91$) (all $ps<.05$). In contrast, cathodal stimulation did not affect learning compared to sham stimulation ($p=.30$). For the multiplication problems, none of stimulation conditions led to performance changes relative to the other stimulation types (all $ps>.05$). Thus, anodal stimulation over PPC specifically improved learning of subtraction problems while not altering learning of multiplication problems.

Performance session

Response latencies

Analysis of response latencies one day after the training revealed that the learning effects were stable across time. Trained problems (1843ms) were solved significantly faster than untrained problems (3032ms; main effect of training: $F(1,57)=524.34$, $p<.001$, $\eta_p^2=.90$). This suggests that the intended transition from effortful procedural to efficient fact retrieval strategies has taken place. As in the training session, multiplications (2350ms) were solved faster than subtractions (2525ms; main effect of operation: $F(1,57)=12.62$, $p=001$, $\eta_p^2=.18$), but this operation effect was only true for the trained problems (1691 vs. 1994ms) and not for the untrained problems (3008 vs. 3056ms) (interaction of training and operation: $F(1,57)=9.56$, $p<.01$, $\eta_p^2=.14$).

Importantly, the impaired learning rates in response latencies during cathodal stimulation in the learning session were still apparent in the performance session one day after the training (interaction of training and stimulation: $F(2,57)=4.00$, $p<.05$, $\eta_p^2=.12$; Fig. 4). In the trained problems, response latencies were slower for participants who had received cathodal stimulation on the previous day (2017ms) compared to anodal (1743 ms; d = 0.55) and sham (1767 ms; d = 0.56) stimulation (both ps<.05). There were no differences between stimulation groups for response latencies on untrained problems (all ps>.05), indicating that stimulation exerted a specific effect on the trained problems. Moreover, similar to the learning session, the cathodal stimulation effects on response latencies for trained problems were not different for the two types of arithmetic operations (interaction of operation and stimulation: $F(2,57)=.17$, $p=.85$, $\eta_p^2=.01$; interaction of training, operation, and stimulation: $F(2,57)=1.23$, $p=.30$, $\eta_p^2=.04$). Finally, similar to the learning session, the anodal group did not significantly differ from the sham group (p>.05). Taken together, this pattern of results suggests that the slowing of learning brought about by cathodal stimulation led to reduced performance for both multiplications and subtractions that persisted for at least 24 hours.

Solution rates

The training was effective at improving performance even 24 hours later, with higher accuracies in the trained (94%) compared to the untrained problems (75%; main effect of training: $F(1,57)=158.47$, $p<.001$, $\eta_p^2=.74$). There was also a significant operation effect ($F(1,57)=11.48$, $p=.001$, $\eta_p^2=.17$) showing a slight performance advantage for multiplications (86 %) over subtractions (83 %).

Comparison of the solution rates for the different stimulation groups did not reveal any significant differences (main effect stimulation: $F(2,57)=1.36$, $p=.26$, $\eta_p^2=.05$; interaction of stimulation and training: $F(2,57)=.61$, $p=.55$, $\eta_p^2=.02$; interaction of stimulation and operation: $F(2,57)=2.71$, $p=.08$, $\eta_p^2=.09$; interaction of stimulation, operation, and training: $F(2,57)=1.49$, $p=.23$, $\eta_p^2=.05$). Thus, the performance benefits on subtraction problems due to anodal stimulation were only evident in the training session but not after 24 hours.

Discussion

The present study shows that tES over the PPC can successfully modulate arithmetic learning. Application of tDCS over the PPC affected the learning progress, both in terms of response latencies and solution rates. Cathodal tDCS decreased learning rates in terms of response latencies, and this effect was still apparent 24 hours after the learning session and was specific to the trained problems. In addition, as hypothesized, anodal tDCS improved solution rates, but this effect emerged specifically in the subtraction but not the multiplication problems.

The finding of a beneficial effect of tDCS on subtraction learning extends previous studies (Clemens *et al.*, 2013; Hauser *et al.*, 2013; Klein *et al.*, 2013; Artemenko *et al.*, 2015) by showing that *not only arithmetic performance but also arithmetic learning* can be enhanced by means of non-invasive brain stimulation over the PPC. Specifically, we found a learning improvement in the subtraction solution rates of 19% after anodal stimulation compared to 6% after sham stimulation. Interestingly, this effect was specific for subtractions and did not emerge for multiplications. The task-dependency of anodal stimulation over the PPC is generally consistent with results of two previous tDCS studies on arithmetic performance, where a positive effect of anodal stimulation on arithmetic performance was only found for subtractions (Hauser *et al.*, 2010) but not for multiplications (Clemens *et al.*, 2013). **Importantly, we demonstrate this dissociation directly within the same experiment and participants, which further strengthens the notion of a neuro-cognitive dissociation between multiplication and subtraction problems in the PPC. This is in line with neuropsychological studies describing patients who are more severely impaired in either their multiplication or their subtraction performance (for a review, Domahs & Delazer, 2005). In addition, our findings corroborate neuroimaging studies that revealed differential activation patterns during the solution**

and the learning of multiplication and subtraction problems (for reviews, cf. Dehaene *et al.*, 2003; Zamarian *et al.*, 2009).

In general, our findings also add to a small but increasing body of evidence that anodal tDCS over the PPC does not universally enhance mathematic performance and learning. Rather, its effect seems to depend on the neuro-cognitive processes involved in a (training) task or may concern only some of these processes. With respect to learning performance, Iuculano and Cohen Kadosh (2013) applied tDCS over the PPC (left anodal plus right cathodal) or the dorsolateral prefrontal cortex (DLPFC; left anodal plus right cathodal) while adults were required to learn artificial numerical symbols over 6 sessions. Interestingly, they found that the learning rate (in reaction time) was highest for PPC stimulation and lowest for DLPFC stimulation, but that the automatic processing of the acquired numerical symbols (at the end of the experiment) displayed the reverse effect: it was highest after DLPFC and lowest after PPC stimulation. This finding indicates that the enhancement of one cognitive function during learning can take place at the expense of others. A similar dissociation was recently reported for arithmetic performance (Rütsche *et al.*, 2015). They found that anodal tDCS over the left PPC resulted in performance improvements (i.e., faster reaction times) in more complex two-digit arithmetic problems (additions and subtractions) but led to impaired performance (in terms of solution rates) in simple one-digit problems. The analysis of brain activity during problem solving (as assessed by means of electroencephalography; EEG) revealed that these differential effects were related to modulations of oscillatory EEG activity in different frequency bands, which are associated either with procedural (alpha band) or memory-based (theta band) or memory-based arithmetic processes. Furthermore, anodal tDCS over the PPC has also been shown to affect specific arithmetic-related processes rather than overall performance (Klein *et al.*, 2013; Artemenko *et al.*, 2015). For instance, Artemenko *et al.* (2015) reported that right anodal (compared to cathodal) stimulation of the PPC resulted in a larger carry effect in two-digit addition problems (i.e., larger reaction time

difference between carry and no-carry problems) without significantly changing overall reaction times.

The aforementioned and the present findings have important implications for current discussions about tDCS as potential method to support arithmetic skill acquisition in individuals with mathematical learning disorders. They suggest that only some neuro-cognitive processes related to successful skill acquisition can be enhanced, which in turn requires the careful examination of the individual's neuro-cognitive deficits and of potential neuro-cognitive side effects due to the stimulation protocol. However, it should also be emphasized that these implications derive from studies of adults without mathematical learning disorders. It is therefore unclear how these effects may generalize to dyscalculic individuals (children and adults) is questionable. To our knowledge, only one study has evaluated tDCS effects on mathematics learning in dyscalculics (Iuculano & Cohen Kadosh, 2014). Two dyscalculic adults received either right anodal plus left cathodal or left anodal plus right cathodal tDCS over the PPC while they were trained on artificial numerical symbols. Interestingly, while in healthy adults right anodal plus left cathodal stimulation enhanced learning (Cohen Kadosh *et al.*, 2010), only the dyscalculic adult who received left anodal plus right cathodal stimulation resulted in performance improvements. This finding clearly highlights the need for further studies in this domain with both healthy and clinical populations.

In contrast to the anodal stimulation condition, cathodal tDCS over the PPC decreased learning rates in terms of response latencies for both types of arithmetic operations. Notably, the present study is the first to show an inhibitory effect of PPC stimulation on arithmetic learning. In the performance session, one day after the training, participants who received cathodal tDCS over the PPC still performed worse in problem-solving compared to those who received anodal or sham tDCS. These effects of cathodal tDCS on arithmetic learning suggest that the PPC plays a causal role in the acquisition of arithmetic skills.

In the domain of mathematical competencies, a few other studies have even revealed a longer temporal stability (up to 6 months) of tES effects on basic number processing (Cohen Kadosh *et al.*, 2010; Cappelletti *et al.*, 2013) and on arithmetic learning (tES over the frontal cortex; Snowball *et al.*, 2013). In all three studies, however, an intensive multi-session training (5 to 6 sessions of 60 to 120 min. per session) was administered. The present findings reveal that even a single-session application of tDCS can modulate the learning success beyond the training session. The observed interaction with the training status of the problems revealed that the stimulation effects were specific to the problems learned during stimulation and did not generalize to untrained problems.

A critical question in the modulation of arithmetic performance and learning by means of tES concerns the stimulation site. In the present study, we focused on the left PPC as this brain region has been consistently associated with arithmetic performance and learning (Ansari, 2008). In the only other arithmetic learning study with tES (Snowball *et al.*, 2013), tES over the bilateral frontal cortex was applied. Although the frontal cortex is frequently involved in arithmetic problem solving in addition to the PPC, it is assumed to support more task-unspecific, generic functions (e.g., working memory processes; Arsalidou & Taylor, 2011). Nonetheless, Snowball et al. found enhanced learning rates in both a fact-based and a calculation-based (procedural) training and did not observe stimulation effects on two control tasks (focusing on mental rotation and attention). However, since they applied transcranial random noise stimulation (tRNS; Guleyupoglu *et al.*, 2013) which involves no constant anode and cathode, no inhibitory effects of tES could be investigated. In addition, their training involved artificial material, for which learning may more strongly rely on task-unspecific frontal brain regions than the real arithmetic problems used in the present study.

Conclusions

In this study, we found that tES over the PPC, a key region in arithmetic processes, modulates success in arithmetic learning. Anodal tDCS specifically enhanced learning rates in subtraction, but not multiplication problems, which adds to current evidence that the beneficial effects of tES depend on the involved neuro-cognitive mechanisms. Cathodal tDCS, in contrast, impaired learning and had an impact on the knowledge application even 24 hours after the stimulation. The present findings reveal that the PPC plays a causal role in arithmetic learning and encourage a further systematic evaluation of the effects of tES over the PPC to support the development of mathematical competencies and the treatment of individuals with mathematical learning disabilities.

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Tables

Table 1

Comparison of models describing the learning improvements. P_p: posterior probability; x_p: exceedance probability

	subtractions			multiplications		
	RMSD	p_p	x_p	RMSD	p_p	x_p
reaction times:						
power law	235.9±114.0	.532	**.953**	189.1±103.8	.684	**1.000**
exponential	233.2±84.6	.338	.047	255.8±104.9	.277	.000
linear	288.6±127.2	.129	.000	323.8±145.2	.036	.000
solution rates:						
power law	.0197±.0665	.339	.367	.0065±.0361	.337	.359
exponential	.0205±.0676	.330	.314	.0007±.0402	.330	.316
linear	.0204±.0675	.331	.320	.0070±.0393	.332	.325

Figure captions

Fig. 1. Time-course of one trial in the learning session.

Fig. 2. Modelling of current density. (a) Electrode positions. (b) Left-hemispheric and frontal views of the simulated current density (given in mA/cm²).

Fig. 3. Learning session: Performance improvements (+/-1 SE) in (a) response latencies and (b) solution rates in both operations (left: multiplication; right: subtraction) as a function of stimulation condition.

* $p < .05$.

Fig. 4. Performance session (24h after training): Response latencies for the trained and untrained problems (collapsed across operations) as a function of the stimulation condition during the learning session.

* $p < .05$.

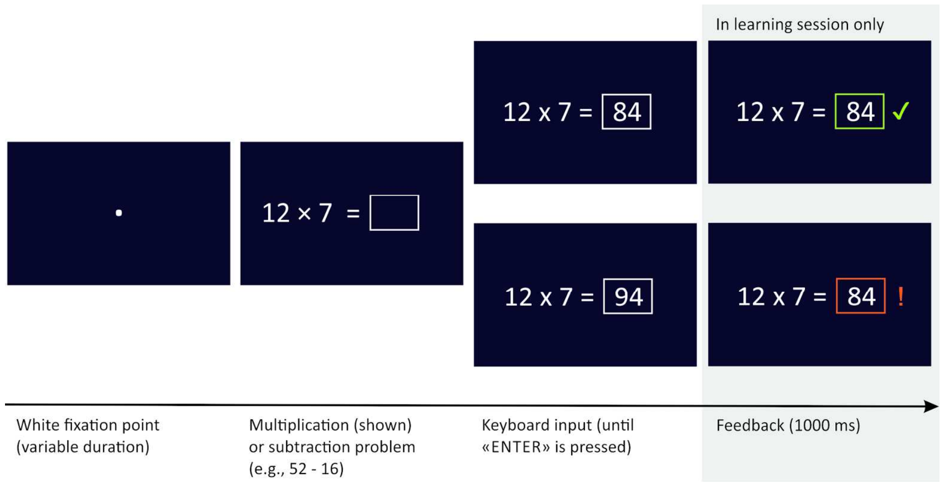


Fig. 1. Time-course of one trial in the learning session.
183x94mm (300 x 300 DPI)

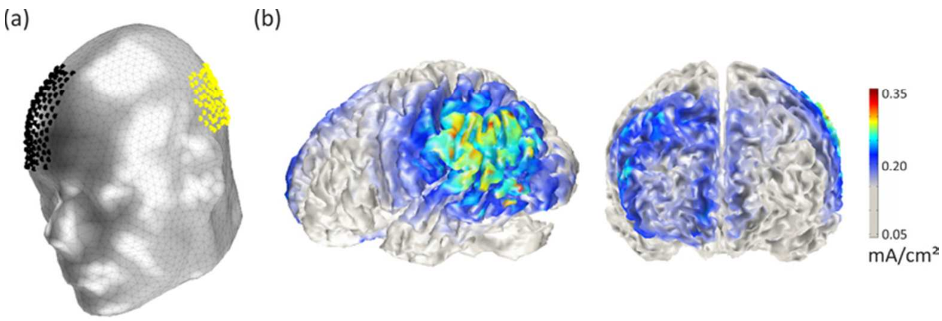


Fig. 2. Modelling of current density. (a) Electrode positions. (b) Left-hemispheric and frontal views of the simulated current density (given in mA/cm²).
64x22mm (300 x 300 DPI)

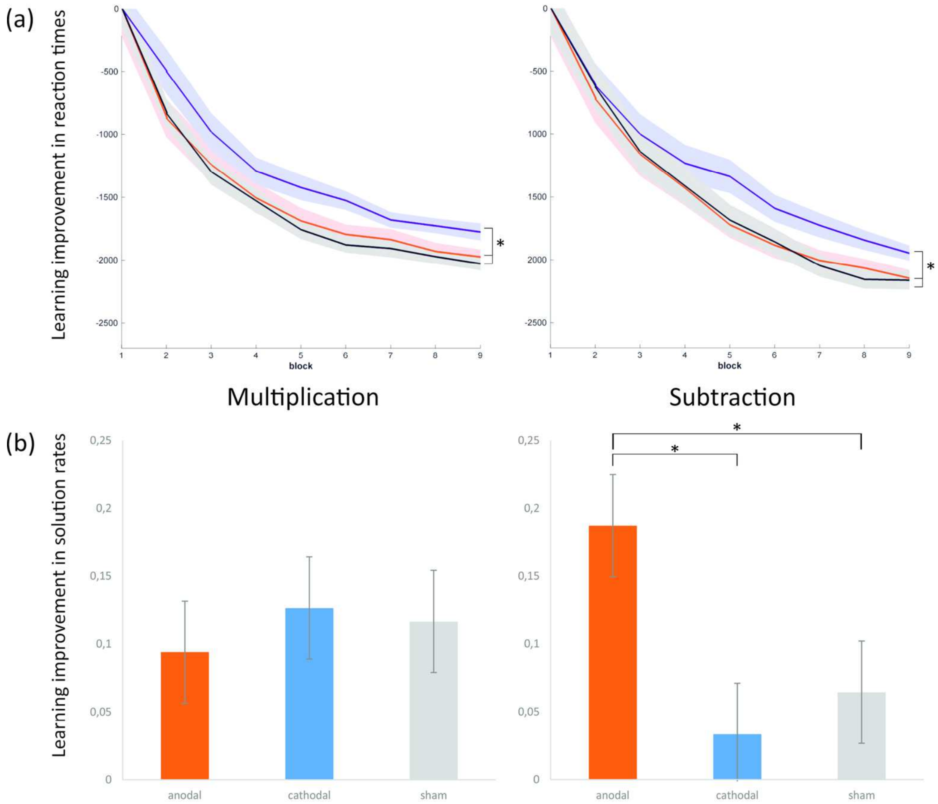


Fig. 3. Learning session: Performance improvements (+/-1 SE) in (a) response latencies and (b) solution rates in both operations (left: multiplication; right: subtraction) as a function of stimulation condition.
* p < .05.
170x150mm (300 x 300 DPI)

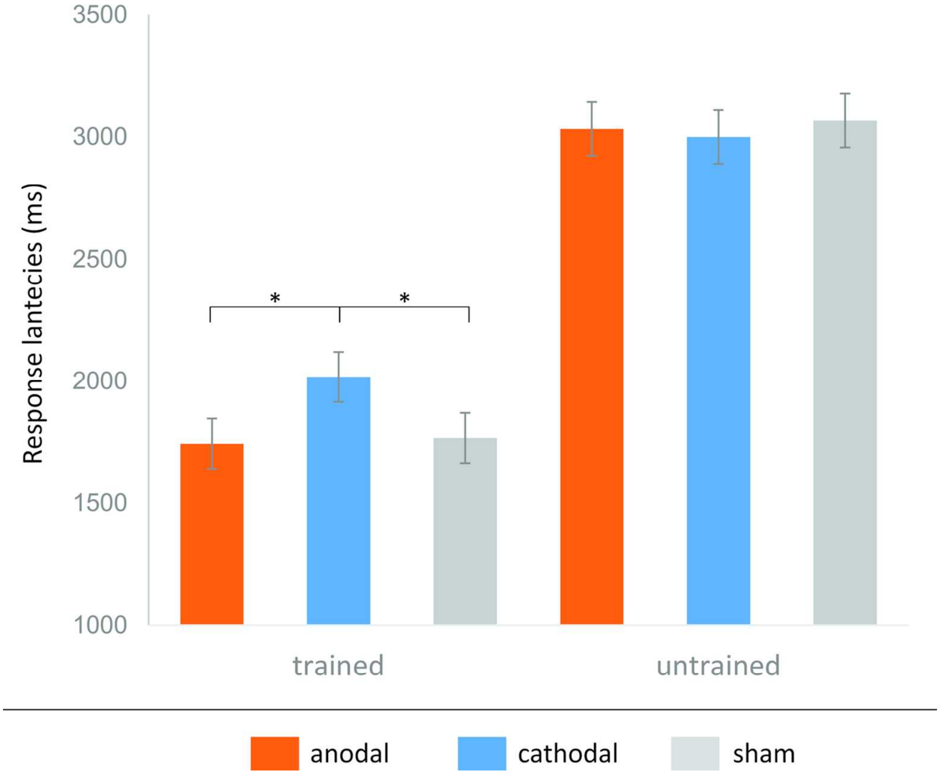
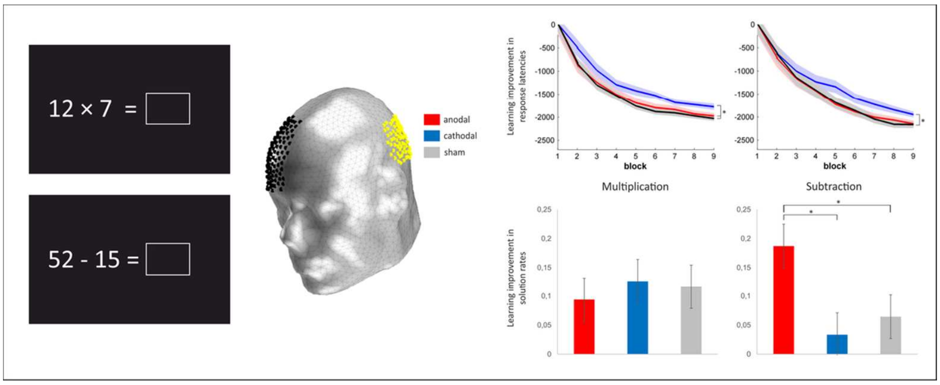


Fig. 4. Performance session (24h after training): Response latencies for the trained and untrained problems (collapsed across operations) as a function of the stimulation condition during the learning session.
* $p < .05$.
123x103mm (300 x 300 DPI)

This study reveals that a single-session application of transcranial direct current stimulation (tDCS) over the left posterior parietal cortex (PPC) can modulate arithmetic learning success, suggesting that the left PPC is causally involved in arithmetic skill acquisition. Cathodal tDCS impaired learning during a 45 min. training session (of multiplications and subtractions) and resulted in poorer performance 24 hours after stimulation. Anodal tDCS improved learning of subtraction problems.



Graphical Abstract Figure
105x42mm (300 x 300 DPI)